

New data on the age and geographic distribution of Neoproterozoic plutons near Saint John, New Brunswick

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New U-Pb zircon and titanite ages for four plutons from the Brookville and Mascarene blocks of the Saint John region suggest that the age distribution of Neoproterozoic intrusions in the Mascarene block resembles that in the Caledonia block, with older plutons emplaced at ~630–620 Ma (Brittain Creek, 625 ± 2 Ma, U-Pb zircon and titanite; Lingley, 629.3 ± 0.9 Ma, U-Pb zircon), and younger plutons emplaced at about 550 Ma. Older plutons are more fractured and altered than younger ones, but not everywhere more strongly foliated. Within the Brookville block, the Hanson Stream pluton gives an age of $532 \pm 1/3$ Ma (U-Pb zircon), demonstrating that $^{40}\text{Ar}/^{39}\text{Ar}$ ages as young as ca. 518 Ma from this pluton (Dallmeyer and Nance 1992) indicate post-emplacement disturbance. The A-type Harvey Hill pluton, previously thought to be the youngest pluton in the Brookville block, gave a U-Pb zircon age of 544 ± 4 Ma, similar to that of the geochemically similar Bonnell Brook pluton of the Caledonia block. Combined with presence of a distinctive Cambro-Ordovician siliciclastic cover (Saint John Group), these dates indicate that the Mascarene and Caledonia blocks originated in the same continental fragment. Western parts of the Brookville and Mascarene blocks were affected by a Cambrian thermal event (520–510 Ma), which may also be represented in the Caledonia block. Tectonic models based on these data suggest that the Saint John region underwent repeated subduction in Neoproterozoic time and diverse transcurrent movements from Silurian to Carboniferous time.

Les nouvelles datations au U-Pb obtenues à partir de zircon et de sphène dans le cas de quatre plutons provenant des massifs de Brookville et de Mascarene dans la région de Saint-Jean permettent de supposer que la répartition des âges des intrusions néoproterozoïques du massif de Mascarene ressemble à celle du massif de Caledonia : la mise en place des plutons les plus âgés remonte à environ 630 à 620 M.A. (crique Brittain, 625 ± 2 M.A., U-Pb à partir de zircon et de sphène; Lingley, $629,3 \pm 0,9$ M.A., U-Pb à partir de zircon) et celle des plus jeunes, à environ 550 M.A. Les plutons les plus âgés sont plus fracturés et altérés que les plus récents, mais ils sont toujours plus fortement feuilletés. À l'intérieur du massif de Brookville, le pluton du ruisseau Hanson affiche un âge de $532 \pm 1/3$ M.A. (U-Pb à partir de zircon), ce qui démontre que les datations à partir de $^{40}\text{Ar}/^{39}\text{Ar}$ de seulement 518 M.A. obtenues de ce pluton (Dallmeyer et Nance 1992) témoignent d'une perturbation ultérieure à la mise en place. Le pluton de type A de la colline Harvey, auparavant considéré comme le pluton le plus jeune du massif de Brookville, a inscrit un âge de 544 ± 4 M.A. par datation U-Pb à partir de zircon, ce qui est analogue à l'âge du pluton à structure géochimique semblable du ruisseau Bonnell du massif Caledonia. Ces âges, combinés à la présence d'une couverture silicoclastique du Cambro-Ordovicien (groupe de Saint-Jean), révèlent que les massifs de Mascarene et de Caledonia proviennent du même fragment continental. Les parties occidentales des massifs de Brookville et de Mascarene ont été affectées par un phénomène thermal Cambrien (520–510 M.A.), qui pourrait aussi être représenté dans le massif de Caledonia. Des modèles tectoniques basés sur ces données laissent supposer que la région de Saint-Jean a été soumise à une subduction répétée à l'époque du Protérozoïque supérieur et à des mouvements de décrochement divers du Silurien au Carbonifère.

[Traduit par la rédaction]

INTRODUCTION

The Avalon Zone of the Canadian Appalachians forms a collage of diverse, fault-bounded fragments (Williams 1995; Nance and Thompson 1996). Many of the fault slices exhibit little metamorphism and possess a Cambro-Ordovician siliciclastic cover sequence with a distinctive stratigraphy and fauna (Landing 1996) which unconformably or disconformably overlies Neoproterozoic igneous rocks. Others exhibit strong metamorphism and lack the cover sequence (Barr and White 1996), while still others contain early to middle Cambrian bimodal volcanic rocks and minor plutons (Keppie and Murphy 1988; Johnson and McLeod 1996). All of the fragments exhibit two or more periods of Neoproterozoic magmatism, commonly with emplacement ages in the ranges 630–600 Ma and 570–545 Ma. A maze of faults of uncertain timing and displacement juxtapose slivers of distinct but apparently related rock assemblages. These complex relations have led to divergent

interpretations of the Avalon Zone, ranging from mid-Paleozoic assembly of fragments with essentially unrelated Neoproterozoic and lower Paleozoic histories (Barr and White 1996) to dissection of a single continental margin over an extended period. (van Staal *et al.* 1996).

All three types of fragments have been defined by recent mapping in the Saint John region (Currie 1997; Barr and White 1999; McLeod *et al.* 1994). Isotopic and geochemical data on plutons within these fragments can be found in Whalen *et al.*, (1994) and Eby and Currie (1996). Previous geochronological data were reviewed by Barr and White (1996). Despite the wealth of data, correlation among the fault-bounded fragments remains controversial. We report here new geochronological data that bear on this question.

GEOLOGICAL SETTING

The Saint John region comprises five northeast-trending,

fault-bounded segments (Fig. 1) which have been termed terranes (Barr and White 1996), but are here designated by the non-committal term 'block', because some of them may be fragments of a common protolith. Three of the four faults separating these blocks (Caledonia, Kennebecasis and Belleisle faults) are steep features with long and complex movement histories, including normal movement in Triassic time, low to high-angle reverse motion in late Carboniferous time, and strike-slip motion in early Carboniferous and older time, with deformation becoming more brittle from southwest to northeast (Helmstaedt 1968; Wardle 1978; Rast and Dixon 1982; Leger and Williams 1986; Currie 1987; Park *et al.* 1994). As a result of complex movement histories, these faults occupy km-scale zones containing numerous movement surfaces of diverse orientation and sense, as well as abundant tectonic inclusions. The fourth fault, the Taylor Brook Fault, is cryptic within the area of Fig. 1, sealed by Siluro-Devonian plutons, but the fault affects the composition of the plutons (McLeod 1990). Farther to the northeast, this fault forms a major lithologic separator, north of which occur slivers of Ordovician mafic volcanic rocks of oceanic affinity (Annidale Group, McLeod *et al.* 1992).

Southeast of the Caledonia Fault, the Caledonia block contains ~630–600 Ma arc-type plutons which exhibit juvenile isotopic signatures (Whalen *et al.* 1994), and a coeval volcanosedimentary sequence (Broad River Group, Barr and White 1996). These rocks, as well as a younger bimodal volcanic rocks (Coldbrook Group) and correlative plutons (~560–550 Ma, Barr *et al.* 1994), are overlain by transgressive, marine, lower Cambrian to lower Ordovician clastic sedimentary rocks (Saint John Group) which bear a distinctive fauna (Landing 1996). Minor amounts of Ordovician and Devonian felsic volcanic rocks occur locally (Barr *et al.* 1994), and fluvial siltstone and conglomerate of the southwesterly-derived Carboniferous Mispic Group (Currie and Nance 1983) unconformably overlie other units along the Bay of Fundy.

Between the Caledonia Fault and the Kennebecasis Fault, plutonic and metamorphic rocks predominate in the Brookville block. The Green Head Group (Wardle 1978), a metasedimentary sequence of Precambrian age, comprises marble, quartzite and minor pelite with olistostromes near the top. The rocks are generally at greenschist facies but reach sillimanite grade along the tectonic contact with the Brookville Gneiss, a narrow rib of tonalitic orthogneiss and high temperature-low pressure paragneiss (White 1995). Detrital zircons from the paragneiss component of the Brookville Gneiss gave a maximum age of ca. 640 Ma (Bevier *et al.* 1990). U-Pb zircon ages show that the orthogneiss component of the Brookville Gneiss was emplaced at ca. 605 Ma and metamorphosed at ca. 564 Ma (Bevier *et al.* 1990). Much of the Brookville block is formed by plutonic suites of three distinct types. One suite has A₂-type chemistry (Eby and Currie 1996), commonly forming high-level aplitic to granophyric bodies. The Musquash pluton of this suite gave a U-Pb zircon age of 550 ± 15 Ma (Currie and Hunt 1991). Another suite ranges from diorite to granite, commonly forming composite bodies which exhibit evidence of mingling of mafic and felsic components (Eby and Currie 1996). This suite was derived from sources similar to those of plutons southeast of the Caledonia fault, with an additional component of old crust (Whalen *et al.* 1994; Eby and Currie 1996). White (1995) obtained a lower U-Pb zircon age of

548 ± 2 Ma from the Fairville pluton, and upper intercept U-Pb zircon and titanite ages of 546 ± 2 from the Ludgate Lake pluton. A third suite comprises more homogeneous quartz diorite and granodiorite and gives distinctly younger ages. White (1995) reported concordant U-Pb zircon and titanite ages of 538 ± 1 Ma for the Rockwood Park pluton and 537 ± 2 Ma for the French Village pluton, and found ⁴⁰Ar/³⁹Ar ages as young as 511 Ma for similar plutons (Renforth and Rockwood Park plutons). In the western part of the Brookville block, Dallmeyer and Nance (1992) reported ⁴⁰Ar/³⁹Ar ages as young as 518 Ma from the Hanson Stream pluton. Volcanic rocks approximately coeval with the older plutons (ca. 555 Ma, Zain Eldeen *et al.* 1991) occur in fault blocks west of Musquash Harbour. Numerous northeast-trending fault slivers of Saint John Group occur in the Brookville block east of Musquash Harbour. The Carboniferous Mispic Group and Kennebecasis Formation, and Triassic Lepreau Formation, all mainly non-marine red-beds, overlie the plutonic suites unconformably.

Bounded by the Kennebecasis and Belleisle faults, the Kingston block consists of sheeted bimodal dykes and correlative volcanic rocks and plutons of the Silurian Kingston Complex (438–435 Ma, Doig *et al.* 1990; Eby and Currie 1993; McLeod *et al.* 1994; Barr *et al.* 1997). Rare screens of meta-sedimentary rocks were possibly derived from the Green Head Group (Currie 1987). Dike trends are rotated counter-clockwise from the trend of the bounding faults, implying emplacement during sinistral transtension (Currie 1987; Doig *et al.* 1990). The central part of the complex is in greenschist facies but grade declines towards the margins (Nance and Dallmeyer 1993).

Between the Belleisle and Taylor Brook faults, the Mascarene block (Fyffe and Fricker 1987) consists of a southern belt of Neoproterozoic and Cambrian rocks (New River belt of McLeod *et al.* 1994; Barr *et al.* 1997), intruded on its northern side by voluminous, lobate Siluro-Devonian plutons which form an elongate array along the trace of the Taylor Brook Fault. In the northeastern part of the Mascarene block, the Cambrian to lower Ordovician siliciclastic Saint John Group overlies the Neoproterozoic rocks. In the southwestern part, the Saint John Group is absent, but lower Cambrian bimodal volcanic rocks of the Buckman Creek formation (Helmstaedt 1968; Johnson *et al.* 1993; Currie 1997) rest unconformably on Neoproterozoic plutons. Prior to this study, no ages greater than ca. 555 Ma (Currie and Hunt 1991; McLeod *et al.* 1994) were known from the Mascarene block. The Siluro-Devonian volcanosedimentary Mascarene Group unconformably overlies Neoproterozoic and Cambrian rocks. Felsic volcanic rocks in the upper part of the Mascarene Group probably correlate with the voluminous Siluro-Devonian plutons to the north (Payette and Martin 1987).

The Taylor Brook Fault marks the northern boundary of the Avalon Zone (van Staal *et al.* 1996), although isolated fragments of possible Avalonian affinity occur further to the northwest. In the Saint John region, Precambrian rocks are not found north of the Taylor Brook Fault, where the strata consist of Ordovician-Silurian bathyal grey to green lithic wacke, slate and siltstone (Digdeguash, Sand Brook and Flume Ridge formations, Fyffe and Miller 1992), overlain by Late Devonian deposits of the Mount Pleasant caldera (Piskahegan Group, McCutcheon 1990) and intruded by coeval, highly evolved rapakivi granite and porphyry (Mount Douglas pluton, McLeod 1990).

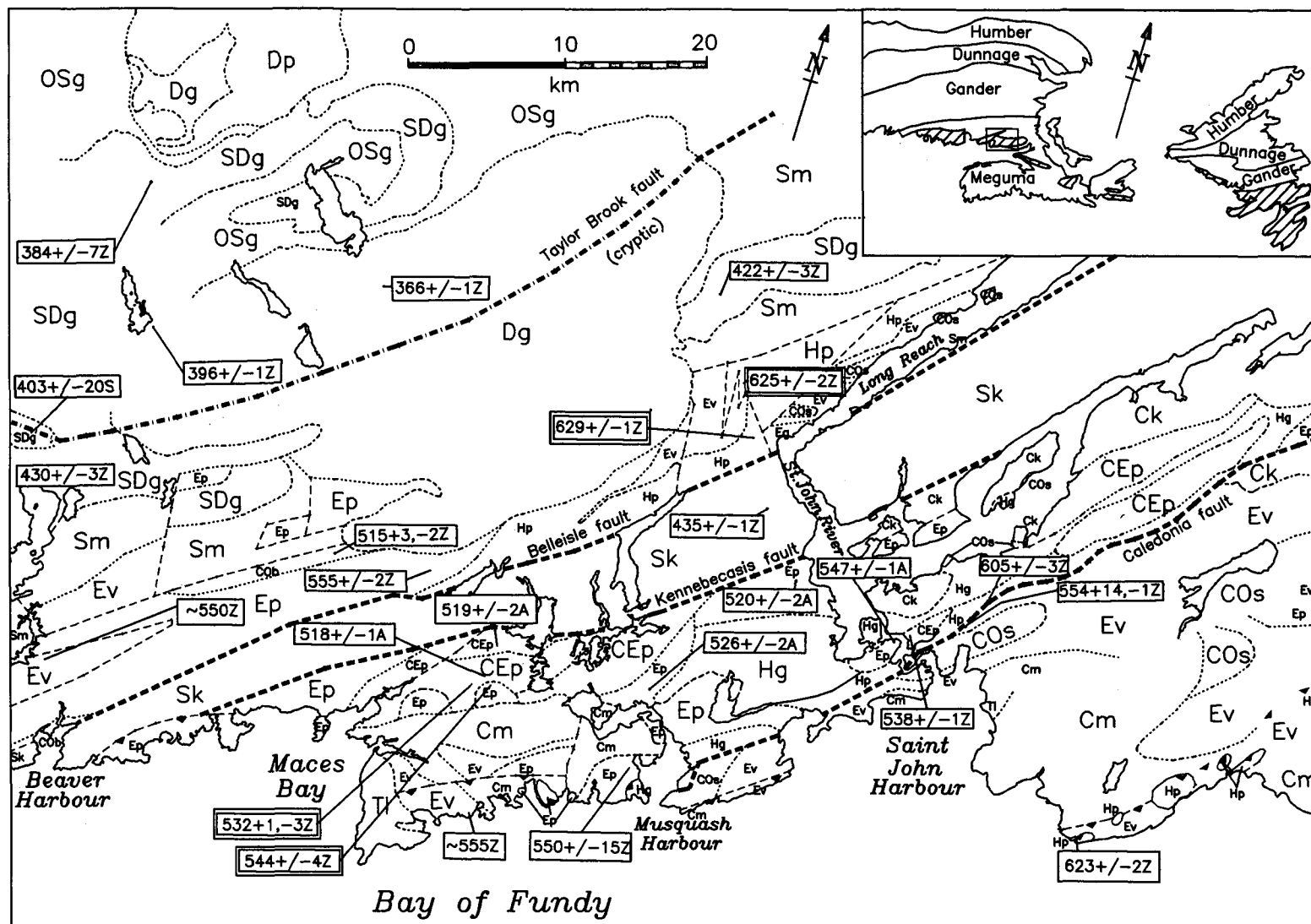


Fig. 1. Simplified geological map of the Saint John region, southern New Brunswick (modified after Currie 1997). The legend (from youngest to oldest) is as follows; TI, Triassic Lepreau Formation (conglomerate); Ck, Carboniferous Kennebecasis Formation (conglomerate); Cm, Carboniferous Mispéc Group (red conglomerate/black siltstone); Dp, Devonian Piskahegan Group (volcanogenic sediments and flows); Dg, Devonian granite and porphyry (Mount Douglas pluton and related rocks); SDg, Siluro-Devonian granite, peralkaline granite, minor gabbro (Welsford, Jake Lee, Utopia, Bocabec and Magaguadavic plutons); Sm, Mascarene Group (siltstone and bimodal volcanic rocks, comagmatic with SDg in part); Sk, Kingston Complex (bimodal sheeted dikes and related plutons and volcanic rocks); OSg, Ordovician and Silurian bathyal wacke and siltstone (Digdeguash, Sand Brook and Flume Ridge formations); COB, Cambrian Buckman Creek Formation (bimodal volcanics, siltstone); COs, Cambro-Ordovician Saint John Group (siltstone, thin ash beds); CEp, Cambrian or Neoproterozoic plutons (540–530 Ma); Ep, Neoproterozoic plutons (555–545 Ma); Ev, Neoproterozoic Coldbrook Group and correlative rocks (~550 Ma, bimodal volcanics); Hp, Neoproterozoic deformed arc-type plutons (625–600 Ma); Hg, Neoproterozoic or older Green Head Group (marble, quartzite, pelite). In the Bay of Fundy thrust belt, teeth are shown on the thrust block. Other faults (dashed lines) exhibit complex motions. Age data are identified by Z for U-Pb zircon determinations, A for $^{40}\text{Ar}/^{39}\text{Ar}$ ages, and S for ages determined by the Rb-Sr method. Sources of data are given in the bibliography. New data are double boxed. The inset map shows the zonal structure of the Canadian Appalachians (Williams 1995), and the location of Avalonian terranes (hachured). The heavy box shows the location of the detailed map.

GEOCHRONOLOGY

On the basis of the preceding observations, we have attempted to answer three specific questions. (i) Does the Mascarene block contain igneous rocks with ages >600 Ma like the other two blocks which contain Neoproterozoic rocks? (ii) Was an A-type granite suite emplaced at ca. 550 Ma in all three terranes, as proposed by Eby and Currie (1996)? (iii) Did igneous activity continue in the Brookville block until <520 Ma?

U-Pb Analytical Methods

Heavy mineral concentrations were prepared by standard crushing, grinding, Wilfley table, and heavy liquid techniques. Mineral separates were sorted by magnetic susceptibility using a Frantz isodynamic separator. U-Pb analytical methods utilized in this study are those outlined in Parrish *et al.* (1987) and Davis *et al.* (1997). Treatment of analytical errors follows Roddick (1987). Analytical results are presented in Table 1, where errors on the ages are reported at the 2 σ level, and displayed in concordia plots (Figs. 2 – 5). The analyzed multigrain zircon fractions were very strongly air abraded following the method of Krogh (1982). U-Pb sample locations are shown in Fig. 1.

Brittain Creek pluton

Currie (1997) mapped a triangular mass of homogeneous coarse-grained, altered tonalite and granodiorite as the Brittain Creek pluton (Fig. 1), which he considered, on the basis of field observations, to be the oldest pluton of the Mascarene block. The mass is bounded on the north by a major fault against Silurian volcanic rocks. To the south, minor faulting disrupts an unconformity against the overlying Saint John Group, and the Neoproterozoic volcanoclastic rocks that disconformably underlie the Saint John Group. To the west, the pluton is truncated against the Lingley pluton along a set of north-northwest and northeast-trending normal faults. The rock has been fractured and brecciated with an intensity that increases toward the southwest. Microscopically, the pluton consists of a subhedral aggregate of altered hornblende and plagioclase with minor chloritised biotite and interstitial quartz. Hornblende has been almost entirely altered to epidote and chlorite. Relics of igneous zoning can be seen in strongly saussuritized plagioclase but the only fresh twinned plagioclase is almost pure albite, obviously of secondary origin. Breccia veins exhibit growth of a second generation of chlorite in vug-like cavities. Zircon and titanite occur as stubby brownish subhedral grains associated with chloritised biotite. Chemical data are not available for the Brittain Creek pluton. The pluton was sampled in road cuts along Highway 177 about 5 km north of Lingley (sample site UTM 19, 713050E, 5028920N).

Five zircon fractions of various morphologies were analyzed from this sample. Fractions A1 and A2 comprised of elongate, euhedral crystals with minor inclusions; fraction B contains clear, stubby, well-faceted prisms. A weighted average of the $^{206}\text{Pb}/^{238}\text{U}$ ages of fractions A1, A2, and B has a value of 625 ± 2 Ma, which is taken to be the best estimate for the crystallization age of the rock (Fig. 2; Table 1). Zircon fraction C contains small, stubby prismatic crystals with numerous fluid inclusions and is interpreted to contain an inherited component. Fraction D, comprised of larger (about 100 microns in size)

Brittain Creek Pluton: CP-96-Z4

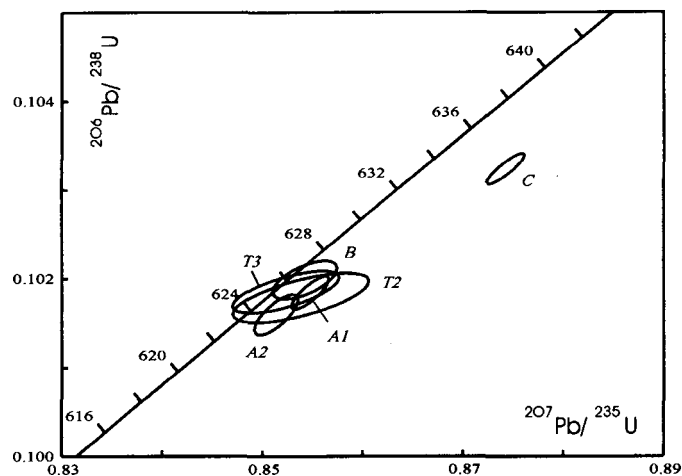


Fig. 2. U-Pb concordia diagram of zircon and titanite analyses, Brittain Creek Pluton (CP-96-Z4).

euhedral, stubby prismatic grains with fluid inclusions, also contains an inherited component and is not plotted on the concordia diagram (see Table 1). Two fractions of subfaceted fragments of light brown (T2) and dark brown (T3) titanite were also analyzed from this sample. A weighted average of the $^{206}\text{Pb}/^{238}\text{U}$ ages of these two analyses is 625 ± 1 Ma, which is in agreement with the interpreted crystallization age of the rock.

Lingley pluton

The Lingley pluton forms one of several elongate masses of quartz-feldspar porphyry extending discontinuously for more than 30 km along the northwest side of the Belleisle Fault (Fig. 1). All are associated with felsic volcanic and minor sedimentary rocks, and petrographically closely resemble one another, but complex faulting in this region makes it difficult to state unequivocally that they are all correlative, or parts of a once continuous body. The porphyry exhibits a distinctive ivory to greenish-ivory shade, in some cases with pink flecks. In thin section the rock contains about 15 percent of corroded quartz phenocrysts, commonly cracked or reduced to fragments, and a few strongly altered plagioclase phenocrysts in a fine-grained matrix of quartz and strongly sericitised feldspar, with small fragments of cognate fine-grained felsic rocks, and rare, small inclusions of a mature quartz sandstone of unknown origin. Like the Brittain Creek pluton, the Lingley pluton was shattered by later deformation, but in this case the shattering appears to have been imposed on a rock which already contained a large number of fragments. Eby and Currie (1996) showed that the Lingley pluton is of A₂-type, and chemically resembles the Fairville pluton of the Brookville block (U-Pb zircon age 548 ± 2 Ma), and the Bonnell Brook pluton of the Caledonia block (U-Pb zircon age 550 ± 1 Ma). On this basis, they suggested that the Lingley pluton might have an age of ~550 Ma. The Lingley pluton was sampled in large new road cuts along Highway 7 about 2 km northwest of Lingley (sample site UTM 19, 714900E, 5026650N).

Five zircon fractions were analyzed, representing various zircon populations in the sample. Zircon fractions B1 and B2 contain water clear, well faceted, stubby prisms. A weighted average of the $^{206}\text{Pb}/^{238}\text{U}$ ages of concordant fraction B1 and

Table 1. U-Pb analytical data

Fraction ^a	Wt. ^b µg	U ppm	Pb ^c ppm	²⁰⁶ Pb/ ²⁰⁴ Pb ^d	Pb ^e pg	²⁰⁸ Pb/ ²⁰⁶ Pb ^f	Radiogenic ratios (±1σ, %) ^g			Ages (Ma, ±2σ) ^h		
							²⁰⁶ Pb/ ²³⁸ U	²⁰⁷ Pb/ ²³⁵ U	²⁰⁷ Pb/ ²⁰⁶ Pb	²⁰⁶ Pb/ ²³⁸ U	²⁰⁷ Pb/ ²³⁵ U	²⁰⁷ Pb/ ²⁰⁶ Pb
Brittain Creek Pluton (CP-96-Z4)												
A1	12	153.9	17.32	4001	3	0.22	0.1018 ± 0.09	0.8548 ± 0.11	0.06087 ± 0.06	625.2 ± 1.1	627.3 ± 1.0	634.7 ± 2.7
A2	8	181.9	20.95	2704	3	0.26	0.1016 ± 0.11	0.8514 ± 0.13	0.06078 ± 0.09	623.8 ± 1.3	625.4 ± 1.2	631.3 ± 3.7
B	7	123.9	14.20	1473	4	0.24	0.1020 ± 0.10	0.8543 ± 0.19	0.06075 ± 0.15	626.0 ± 1.2	627.0 ± 1.8	630.4 ± 6.4
C	21	196.9	23.19	3305	8	0.26	0.1032 ± 0.08	0.8742 ± 0.11	0.06142 ± 0.05	633.4 ± 1.0	637.9 ± 1.0	653.8 ± 2.1
D	14	186.0	25.79	4885	4	0.22	0.1236 ± 0.09	1.4925 ± 0.10	0.08760 ± 0.05	751.1 ± 1.2	927.3 ± 1.2	1373.7 ± 1.8
T2	49	131.8	26.40	411	104	1.22	0.1018 ± 0.14	0.8538 ± 0.40	0.06084 ± 0.32	624.9 ± 1.6	626.7 ± 3.7	633.6 ± 14
T3	68	144.4	31.28	527	122	1.40	0.1018 ± 0.12	0.8523 ± 0.31	0.06069 ± 0.25	625.2 ± 1.4	625.9 ± 2.9	628.4 ± 11
Lingley Pluton (CP-96-Z3)												
A1	10	306.0	38.54	865	26	0.16	0.1193 ± 0.10	1.1381 ± 0.20	0.06919 ± 0.15	726.5 ± 1.3	771.6 ± 2.1	904.4 ± 6.0
A2	11	359.6	41.98	1130	23	0.19	0.1085 ± 0.09	0.9617 ± 0.17	0.06428 ± 0.11	664.1 ± 1.2	684.2 ± 1.7	750.9 ± 4.8
B1	9	260.1	28.68	3408	5	0.19	0.1026 ± 0.10	0.8591 ± 0.13	0.06074 ± 0.08	629.6 ± 1.2	629.6 ± 1.2	629.9 ± 3.3
B2	11	354.6	38.66	2035	12	0.18	0.1025 ± 0.09	0.8598 ± 0.13	0.06085 ± 0.08	629.0 ± 1.1	630.0 ± 1.2	633.8 ± 3.5
C1	20	272.0	29.96	5841	6	0.18	0.1028 ± 0.09	0.8620 ± 0.10	0.06083 ± 0.04	630.7 ± 1.0	631.2 ± 1.0	633.2 ± 1.8
Hanson Stream Pluton (CP-96-Z2)												
B1	10	630.8	60.10	6863	20	0.23	0.08600 ± 0.09	0.6904 ± 0.11	0.05822 ± 0.04	531.8 ± 0.9	533.0 ± 0.9	538.1 ± 1.8
C1	10	329.2	31.60	6125	12	0.24	0.08599 ± 0.15	0.6892 ± 0.15	0.05813 ± 0.09	531.8 ± 1.6	532.3 ± 1.3	534.8 ± 3.9
C2	10	375.4	35.66	19510	4	0.23	0.08558 ± 0.10	0.6848 ± 0.11	0.05803 ± 0.04	529.4 ± 1.0	529.7 ± 0.9	531.1 ± 1.8
C3	42	192.8	18.56	8673	5	0.24	0.08597 ± 0.08	0.6887 ± 0.10	0.05811 ± 0.04	531.6 ± 0.8	532.0 ± 0.8	533.8 ± 1.8
T2	472	224.3	21.80	1332	438	0.24	0.08675 ± 0.10	0.6973 ± 0.22	0.05829 ± 0.18	536.3 ± 1.0	537.2 ± 1.9	540.8 ± 8.0
T3	244	137.5	13.29	998	183	0.25	0.08550 ± 0.10	0.6856 ± 0.20	0.05816 ± 0.14	528.9 ± 1.0	530.2 ± 1.7	535.7 ± 6.3
Harvey Hill Pluton (CP-96-Z1)												
A	15	154.4	15.21	197	70	0.24	0.08838 ± 0.27	0.7137 ± 0.93	0.05857 ± 0.77	545.9 ± 2.9	546.9 ± 7.9	551.1 ± 33
C	12	131.1	12.55	2137	4	0.20	0.08803 ± 0.12	0.7107 ± 0.14	0.05855 ± 0.10	543.9 ± 1.2	545.2 ± 1.2	550.5 ± 4.2
D	10	106.7	10.09	1585	4	0.19	0.08775 ± 0.21	0.7127 ± 0.24	0.05891 ± 0.20	542.2 ± 2.1	546.3 ± 2.0	563.6 ± 8.7
T1	25	71.4	10.76	165	65	0.96	0.08666 ± 0.29	0.7079 ± 1.01	0.05924 ± 0.86	535.8 ± 3.0	543.5 ± 8.5	576.0 ± 37
T2	22	70.4	9.59	238	37	0.78	0.08567 ± 0.23	0.6944 ± 0.74	0.05878 ± 0.62	529.9 ± 2.3	535.4 ± 6.2	559.0 ± 27
T3	42	75.7	11.28	191	99	0.94	0.08631 ± 0.27	0.6985 ± 0.94	0.05870 ± 0.78	533.7 ± 2.7	537.9 ± 7.9	555.9 ± 34

^a All zircon fractions were strongly abraded; T = titanite.

^b Error on weight is ± 1 µg.

^c Radiogenic Pb.

^d Measured ratio corrected for spike and Pb fractionation of 0.09±0.03%/AMU.

^e Total common Pb on analysis corrected for fractionation and spike.

^f Radiogenic Pb.

^g Corrected for blank Pb and U and common Pb (Stacey-Kramers model Pb composition equivalent to the ²⁰⁷Pb/²⁰⁶Pb age).

^h Corrected for blank and common Pb.

overlapping fraction B2 is 629.3 ± 0.9 Ma (Fig. 3, Table 1). This date is taken to represent the crystallization age of the rock. Fraction C1, composed of elongate euhedral crystals with minor inclusions, is interpreted to contain a minor inherited component. Fractions A1 and A2 are well faceted, stubby prisms selected from a slightly more magnetic zircon population and are interpreted to contain inherited components of possible Middle Proterozoic age.

Hanson Stream pluton

The Hanson Stream pluton forms a large ovoid mass elongated along tectonic strike in the western part of the Brookville block (Fig. 1). The pluton consists of grey, medium

to coarse-grained unfoliated hornblende-biotite granodiorite to monzogranite. Rounded, partly assimilated, mafic inclusions up to 30 cm in diameter are abundant and characteristic. Eby and Currie (1996) reported chemical data for the Hanson Stream pluton. To the east, the pluton intruded tonalite to granodiorite of the Shadow Lake pluton with formation of igneous breccias along the contact. On the basis of map pattern, Currie (1987) deduced that the Harvey Hill pluton intruded the Hanson Stream pluton, but no exposure or definitive evidence of this relation has been found. The Hanson Stream pluton was sampled in large, fresh road cuts along access roads to Highway 1 (sample site UTM 19, 702660E, 5006240N). The sample consists of hypidiomorphic, moderately altered tablets of plagioclase and hornblende, with interstitial mosaic quartz and subordinate green

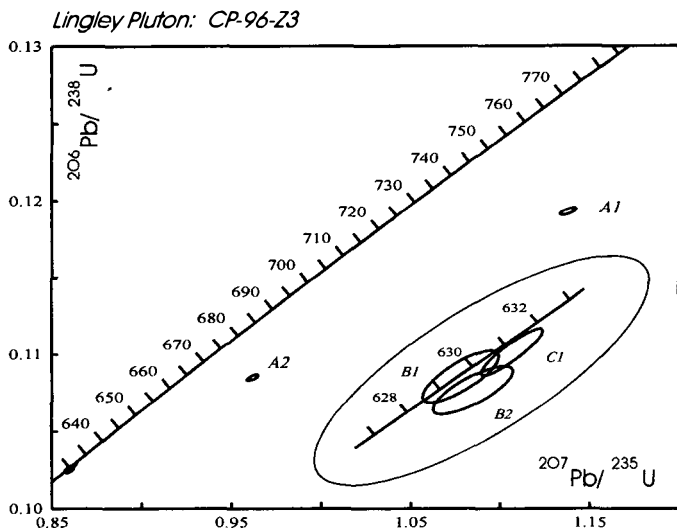


Fig. 3. U-Pb concordia diagram of zircon analyses, Lingley Pluton (CP-96-Z3).

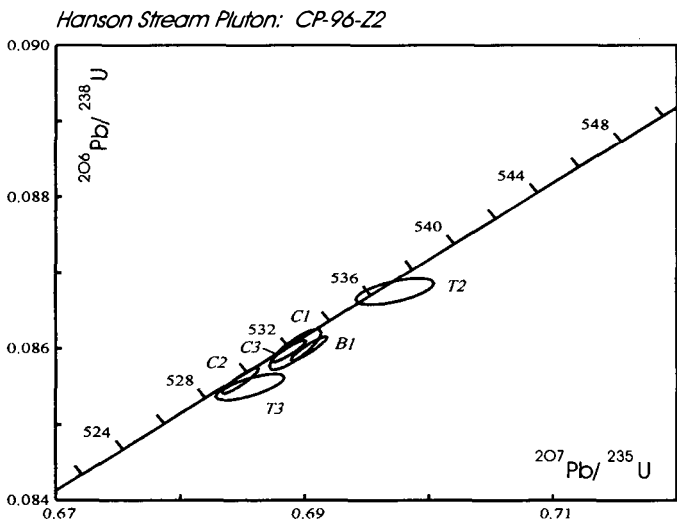


Fig. 4. U-Pb concordia diagram of zircon and titanite analyses, Hanson Stream Pluton (CP-96-Z2).

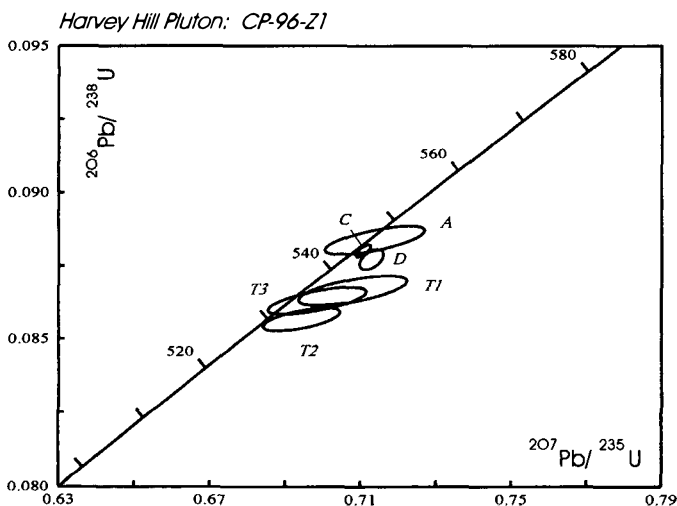


Fig. 5. U-Pb concordia diagram of zircon and titanite analyses, Harvey Hill Pluton (CP-96-Z1).

biotite. Potash feldspar (orthoclase) occurs as large ovoid grains overprinting the other minerals. Zircon occurs as stubby, rounded prisms associated with both biotite and hornblende. Titanite occurs as small subhedral grains in hornblende.

Zircon fractions analyzed from this sample include large (>105 microns), euhedral prisms (B1), euhedral, stubby grains (C1 and C3) and slightly elongate prismatic crystals (C2). Most of the zircons analyzed contain minor fluidal inclusions. Three of the zircons analyses overlap and intersect concordia; a weighted average of the $^{206}\text{Pb}/^{238}\text{U}$ ages of fractions C1, C3, and B1 is 531.7 ± 0.7 Ma (Fig. 4, Table 1). The fourth zircon fraction (C2) intersects concordia and has a $^{206}\text{Pb}/^{238}\text{U}$ age of 529.4 ± 1.0 Ma; this fraction may have undergone a minor amount of Pb loss. The best interpretation for the crystallization age of the rock is taken to be $532 \pm 1/3$ Ma. Two fractions of clear, anhedral, golden brown (T3) and light brown (T2) titanite fragments were analyzed from the sample. One of the analyses possibly contains an inherited component (T2). The age of the second titanite analysis is in agreement with the age of zircon fraction C2 and may also have undergone minor Pb loss.

Harvey Hill pluton

The Harvey Hill pluton forms a subcircular mass of fine to medium-grained, locally porphyritic, red granite and granophyre. No contacts have been found, but the pluton has sharp contacts on radiometric surveys (Shives 1986), and on the basis of this data has been thought to intrude all surrounding pre-Carboniferous rocks. The Harvey Hill pluton exhibits an unusual A₂-type chemistry, as discussed by Eby and Currie (1996). The pluton was sampled in rock cuts along access roads to Highway 1 (sample site UTM 19, E, N). The sample consists of an allotriomorphic aggregate of quartz, microcline and albite with some larger, embayed feldspar grains. Brown to olive green biotite, commonly chloritised, occurs sparingly in single grains or aggregates. Allotriomorphic aggregates of pale buff titanite, commonly associated with magnetite, are almost as abundant as biotite. Zircon occurs as minute stubby prisms in biotite.

This sample contains small, well-faceted, stubby prismatic zircons with fluidal inclusions. Three fractions have overlapping analyses; a weighted average of the $^{206}\text{Pb}/^{238}\text{U}$ ages of fractions A, C, and D is 544 ± 4 Ma (Fig. 5, Table 1). This date is taken to be the crystallization age of the rock. Three fractions of clear, anhedral, light brown titanite fragments were also analyzed from this sample. These analyses give distinctly younger ages, although the weighted average of the three titanite ages, 533 ± 7 Ma (Fig. 5, Table 1), has a 2σ error which just overlaps the 2σ error of the weighted average zircon age. The overlap is so slight that the titanite ages probably reflect a post-emplacement thermal event.

DISCUSSION

Our data clearly show that older rocks, coeval with the Broad River Group, and correlative plutons in the Caledonia block occur in relative abundance in the Mascarene block. Currie (1997) concluded on the basis of field observation that the Britain Creek pluton is the oldest pluton within this block; the age determination of 625 ± 2 Ma agrees with these observations. The age of 629.3 ± 0.9 Ma for the Lingley pluton contradicts the

opinions of both McLeod *et al.* (1994), who considered this pluton to be of Neoproterozoic to Cambrian age, and Eby and Currie (1996), who correlated it with ca. 550 Ma plutons on geochemical grounds. Saint John Group and related strata appear to unconformably overlie the Lingley pluton, but no other clear field evidence of age relationships has been found. Eby and Currie (1992) noted that basalt apparently associated with porphyries of Lingley type is more primitive than basalt of the ~550 Ma Coldbrook Group of the Caledonia block, more closely resembling basalt of the ~625 Ma Broad River Group. The age of the Lingley pluton suggests that similar subvolcanic porphyries and felsic volcanic rocks along the north shore of the Long Reach may have similar ages, rather than the Cambrian ages assumed by McLeod *et al.* (1994). A zircon age of ca. 555 Ma has recently been reported for felsic volcanic rocks on the south shore of the Long Reach (Barr *et al.* 1997), but there appear to be no obvious field criteria for assigning ages to such rocks, a situation similar to that in the Caledonia block (Barr *et al.* 1994).

The age of 532±1/3 Ma for the Hanson Stream pluton, combined with earlier data from the Brookville block, make it clear that the ⁴⁰Ar/³⁹Ar ages of less than 520 Ma in this block do not represent emplacement ages, but post-emplacement thermal events. The ca. 532 Ma age for this pluton confirms that the 540–530 Ma igneous event discovered by Bevier *et al.* (1990) extends the length of the Brookville block. This event significantly post-dated emplacement of A₂-type plutons such as Harvey Hill. Re-examination of thin sections of the latter exhibit a distinct mosaic recrystallisation, now attributed to the effect of intrusion of the Hanson Stream pluton, an event probably also reflected by the relatively young titanite ages (ca. 533 Ma) from the Harvey Hill Pluton. Intrusion of the A₂-type plutons in the Brookville block appears to have been confined to the period 555–545 Ma, preceding an igneous event of different character by ~10 Ma.

Implications for block correlation

Neoproterozoic rocks in the Saint John region occur in the Caledonia, Brookville and Mascarene blocks. Attempts to correlate these fragments have elicited two hypotheses, namely (i) that the three fragments all derive from the same source, are not separated by large lateral displacements, and hence display a common igneous history, or (ii) that the three fragments derive from differing sources, have been juxtaposed by large lateral displacements of post-middle Cambrian age, and hence display diverse Neoproterozoic igneous histories.

In light of previous and present data, derivation of the Mascarene and Caledonia blocks from the same source appears probable. The age distribution of Neoproterozoic igneous rocks is essentially identical in both blocks with emplacement of plutons and volcanics at 630–605 Ma and 570–545 Ma. The stratigraphically distinctive Saint John Group unconformably overlies Neoproterozoic rocks in both slices. In our opinion these facts establish that the two blocks originally came from the same continental fragment, and were attached to that fragment until at least lower Ordovician time (youngest strata of the Saint John Group). This does not imply that the two blocks were originally contiguous. They are separated by three major faults, and may have lain tens or hundreds of km apart. Large-scale relative motions between the Caledonia and Mascarene blocks

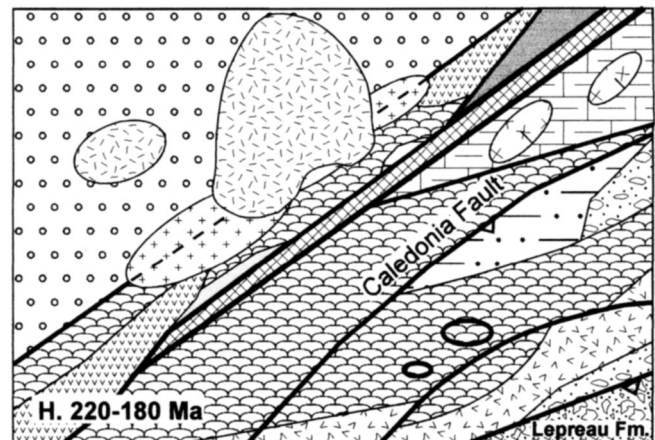
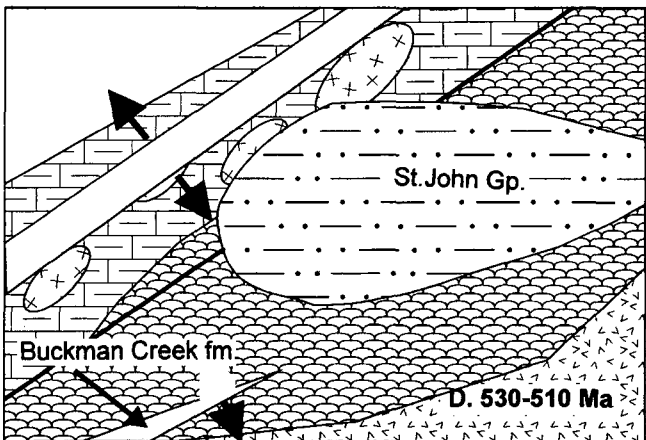
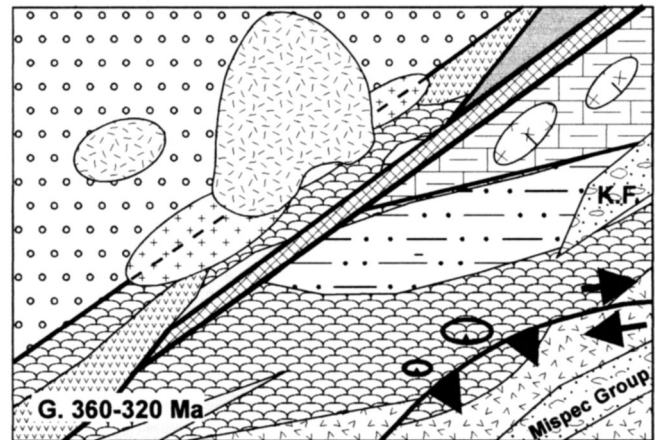
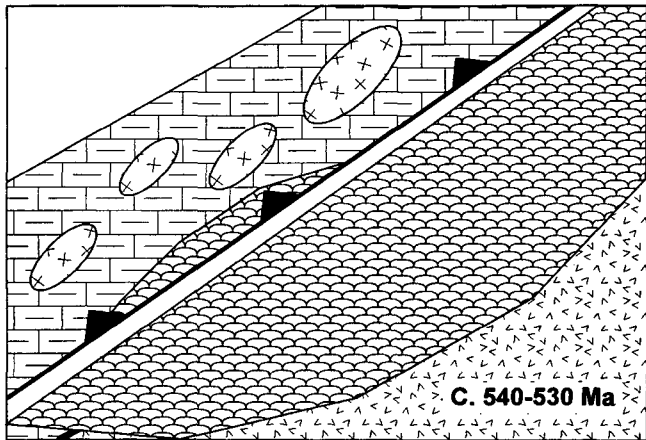
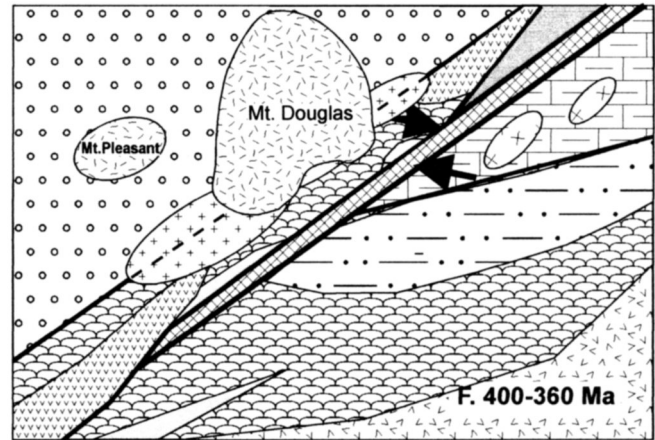
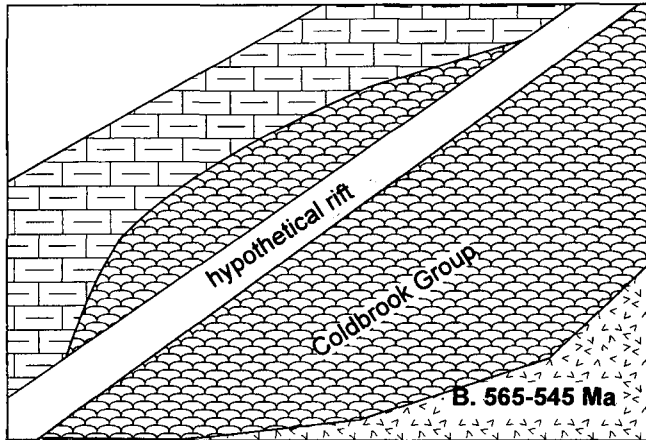
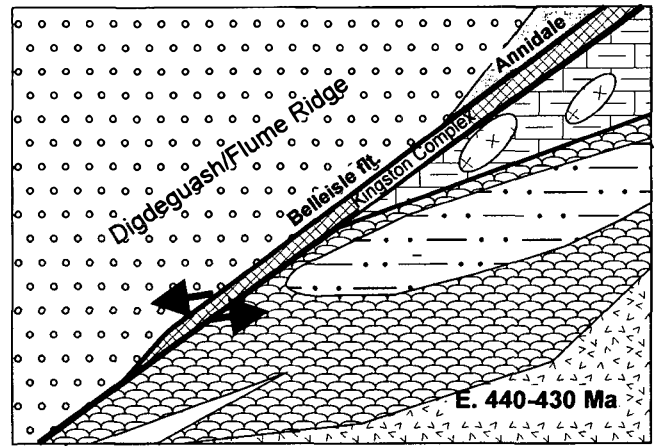
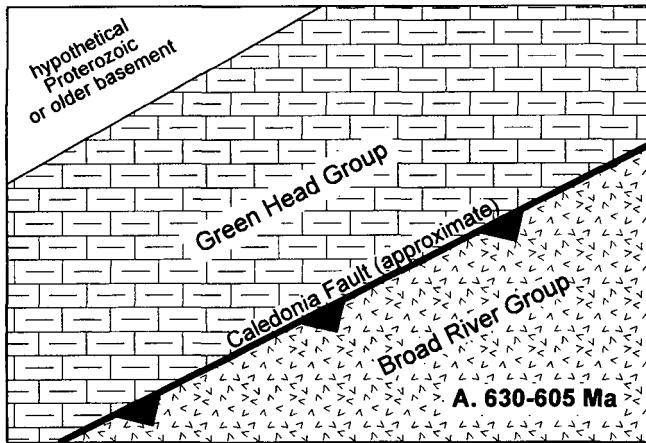
subsequent to lower Ordovician time could be responsible for presence of abundant Siluro-Devonian sedimentary and igneous rocks in the Mascarene block compared to their scarcity in the Caledonia block.

The Brookville block differs from the Caledonia and Mascarene blocks in several respects. The oldest strata within the block, the Green Head Group, are a shelf-type sedimentary sequence which has no correlatives in the Caledonia or Mascarene blocks. The Brookville block exhibits two periods of Neoproterozoic magmatism, but the older period (>600 Ma), while overlapping in age with flanking blocks, appears to be slightly younger. High temperature-low pressure metamorphism at ca. 565 Ma (White 1995), typical of the Brookville block, does not appear in flanking blocks. Younger igneous ages fall into two groups, one ca. 555–545 Ma and the other ca. 540–530 Ma. The former age is well represented in the Caledonia and Mascarene blocks, but the latter has no known correlatives within these blocks. Mid-to late Cambrian thermal disturbance in the Brookville block, indicated by numerous ⁴⁰Ar/³⁹Ar ages <520 Ma (Dallmeyer and Nance 1992; White 1995), is coeval with stratigraphic and radiometric ages (early to middle Cambrian, ca. 510 Ma) of basaltic volcanic rocks in the Mascarene block (Helmstaedt 1968; Johnson *et al.* 1993). Lamprophyric intrusions in the Saint John Group of the Caledonia block may be of similar age.

Despite obvious differences, several lines of evidence indicate that the Brookville block was connected to the Caledonia/Mascarene block by ca. 550 Ma. Igneous rocks of 555–545 Ma age and similar chemical character are found in all three blocks (Whalen *et al.* 1994). Although the Saint John Group and related Neoproterozoic strata are not found in place within the Brookville block, the ubiquitous occurrence of fault slivers (more than a dozen occurrences) implies a stratigraphic or tectonic cover of Saint John Group over much of the Brookville block at some time in the past.

The detailed tectonic history of the Saint John region cannot be unravelled at present. A possible scenario might include the following elements, diagrammed in Fig. 6.

- (a) At about 630–605 Ma, subduction brought a continent or continental fragment with the Green Head Group as a passive margin sequence against a continental margin including the Caledonia and Mascarene blocks, producing extensive arc magmatism in the latter (Broad River Group and correlative plutons including Brittain Creek and Lingley).
- (b) At about 565–545 Ma an intense thermal event involving upwelling of mantle material occurred beneath the former collision zone, possibly as a result of crustal delamination after collision (Whalen *et al.* 1994). This event produced bimodal and A₂-type magmatism (Coldbrook Group and correlative plutons, including Harvey Hill) and accompanying high temperature-low pressure metamorphism.
- (c) From 540–530 Ma, large-scale magmatism occurred in the Brookville block only, implying that the Brookville block separated from the Mascarene-Caledonia block during or shortly after the ca. 550 Ma event. In the model of Whalen *et al.* (1994) this separation was ascribed to rifting and spreading over a mantle upwelling. The subsequent 540–530 Ma magmatism in the Brookville block appears subduction-related (White and Barr 1996), which could be explained by subduction beneath the Brookville block producing a second collision between the



Brookville and Mascarene-Caledonia blocks. In this model the Saint John Group was deposited on a thermally subsiding passive margin subsequent to this collision. Cambrian igneous activity on this margin may indicate further rifting, which left the Brookville block as a tiny remnant attached to the Mascarene-Caledonia block, and facing an oceanic basin in which the Digdeguash, Sand Brook and Flume Ridge formations were deposited.

(d) By 440 Ma this ocean had largely closed by northwest-directed subduction. Post-closure sinistral transtension along the former continent-ocean margin opened pull-apart basins forming sites for the deposition of sedimentary and mafic volcanic rocks (lower Mascarene Group), and the emplacement of sheeted dikes of the Kingston Complex.

(e) At about 430–400 Ma, motion reversed to dextral transpressive. Dextral motion along the northern boundary of the Kingston Complex moved the Mascarene block north of the Brookville block and Kingston Complex from an original position to the southwest (present orientation). The transpressive component of this hypothetical motion may have moved the Mascarene block southward over the relatively fixed mantle magmatic source of the Kingston Complex, causing magmatism to migrate northwest and become more continental in character.

(f) Insulation of the residual mantle upwelling by over-riding crustal material produced a final, climactic igneous outburst 40 million years later (360 Ma), essentially inverting a large part of the crust (Mount Douglas pluton and Mount Pleasant caldera).

(g) Continued dextral transpression produced pull-apart basins, accommodating Carboniferous clastic sequences at releasing bends and thrust allochthons at compressional bends. We assume that the Brookville and Kingston blocks were uplifted and tilted during this process, leaving residual fault slivers of younger rocks as evidence of alternate compressive and extensional motions.

(h) Opening of the Atlantic Ocean produced normal faulting along the Bay of Fundy, opening half-graben basins in which the Triassic Lepreau Formation was deposited, and Saint John Group and Coldbrook Group strata in the Caledonia block preserved by east-side-down motion on the Caledonia Fault.

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Fig. 6. Cartoon of a possible tectonic history for the Saint John region. (a) 630–605 Ma; Subduction beneath a Gondwanan margin, collision with a continent with the Green Head Group as a passive margin sequence, formation of the Broad River Group and correlative plutons. (b) 565–545 Ma; mantle upwelling (due to crustal delamination?) producing bimodal and A_2 -type magmatism (Coldbrook Group and correlative plutons), metamorphism and rifting. (c) 540–530 Ma; Large-scale magmatism (Hanson Stream and correlative plutons) due to subduction beneath the Brookville block, reuniting it with the Mascarene-Caledonia block. (d) 530–510 Ma; Deposition of a Saint John Group on a thermally subsiding margin. Persistent rifting and igneous activity leading to continental break-up. (e) 440–430 Ma; Post-closure sinistral transtension along the former continent-ocean margin, forming pull-apart basins, emplacement of Kingston Complex, deposition of Mascarene Group. (f) 430–360 Ma; Dextral transpressive motion. Emplacement of the Mascarene block and over-thrusting of the Kingston block by the Mascarene block causing magmatism to migrate northwest leading to climactic emplacement of Mount Douglas pluton and Mount Pleasant caldera. (g) 360–320 Ma; Continued dextral transpression, pull-apart basins, filled by clastic sequences, thrust allochthons at compressional bends, fault slivers of Saint John Group formed. (h) 220–180 Ma; Opening of the Atlantic Ocean, normal faulting along the Bay of Fundy, deposition of Lepreau Formation, downfaulting of Caledonia block.

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